Hydrologic Cycle

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The importance of water on Earth cannot be underestimated. Water is transported endlessly throughout the various components of the Earth's climate system, affecting every component along the way. Clouds and water vapor in the atmosphere influence the energy balance of the Earth, and snow and ice-covered surfaces reflect a significant amount of the Sun's radiation back to space. Water at and under the land's surface, in the form of streamflow or groundwater, plays an important role in the maintenance of living organisms and human societies. However, while water is a benefit, if it arrives at the wrong time, in the wrong quantity, or is of poor quality, it can be a severe hazard. To mitigate these hardships, humans have significantly altered the hydrologic cycle with construction of dams, cultivation of farmland, urbanization, draining of swamplands, etc. The local consequences of these changes can be dramatic, leading to environmental changes and, in some cases, local degradation. The global impacts are difficult to ascertain, however. With the increasing demand for freshwater resources and increased societal vulnerability to climate extremes, the effects on humans by water-related global environmental change remain an interesting but as of yet unresolved question.

INTRODUCTION

The hydrologic cycle is the perpetual movement of water throughout the various components of the Earth's climate system. Water is stored in the oceans, in the atmosphere, as well as on and under the land surface. The transport of water between these reservoirs in various phases plays a central role in the Earth's climate. Water evaporates from the oceans and the land surface into the atmosphere, where it is advected across the face of the Earth in the form of water vapor. Eventually, this water vapor condenses within clouds and precipitates in the forms of rain, snow, sleet, or hail back to the Earth's surface. This precipitation can fall on open bodies of water, be intercepted and transpired by vegetation, and become surface runoff and/or recharge groundwater. Water that infiltrates into the ground surface can percolate into deeper zones to become a part of groundwater storage to eventually reappear as streamflow or become mixed with saline groundwater in coastal zones. In this final step, water re-enters the ocean from which it will eventually evaporate again, completing the hydrologic cycle. The hydrologic cycle qualitatively, quantitatively, and conceptually is depicted in Figures 1–3.

The important reservoirs within the hydrologic cycle include:

Ocean

This vast body of salt water covers 70% of the Earth's surface; it stores and circulates enormous amounts of water and energy. In addition, patterns of ocean surface temperatures can exert a strong influence on circulation patterns in the atmosphere. Frequently, the ocean is divided into two parts, an upper and lower zone. The upper zone is considerably warmer and less saline than the lower zone, and the two are separated by a relatively sharp thermocline. The depth from the ocean surface to the thermocline can be as much as 400 m, but is generally less than 150 m.

Atmosphere

Water can be stored in the atmosphere as liquid in clouds or as water vapor. Water vapor content of the atmosphere is described by its humidity. Specific humidity is a measure of the water content per unit of dry atmosphere (typical values are $1-20\,\mathrm{g\,kg^{-1}}$); relative humidity is the amount of water vapor present relative to the amount of water vapor that would saturate the air at a particular temperature. The presence of water in the atmosphere alters the radiation budget of the atmosphere, directly through latent heat and indirectly as both a reflector and absorber of radiation. Water in the atmosphere is the most significant contributor to the natural greenhouse effect.

Cryosphere

The largest stores of fresh water on the Earth are contained in glaciers and icecaps, primarily at high latitudes. The cryosphere has a significant impact on the climate of the Earth because snow and ice-covered surfaces have a very high albedo (comparable to that of clouds). The large volume of runoff from northern high-latitude rivers also influences the Arctic and Atlantic Ocean circulation, which impacts the climate in those regions. Despite the importance of the cryosphere to the hydrologic cycle, relatively little is understood about this part of the climate system, partially because of the lack of adequate data in these often remote and difficult to access areas.

Groundwater

Water beneath the land surface can be classified in a variety of ways. Water closest to the surface (within a few meters) is considered soil moisture, and this water influences the evapotranspiration rate of water from the surface. Soil moisture that is frozen year-round is called permafrost. Deeper below the surface is the aquifer, where the water

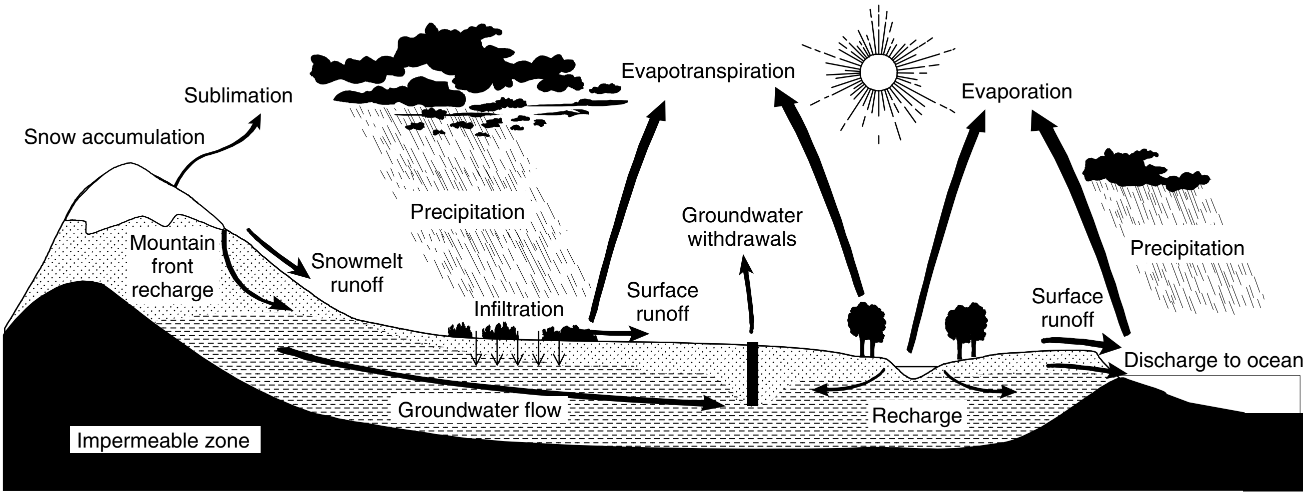

Figure 1 A schematic diagram of various fluxes within the hydrologic cycle. (Figure prepared by B Imam)

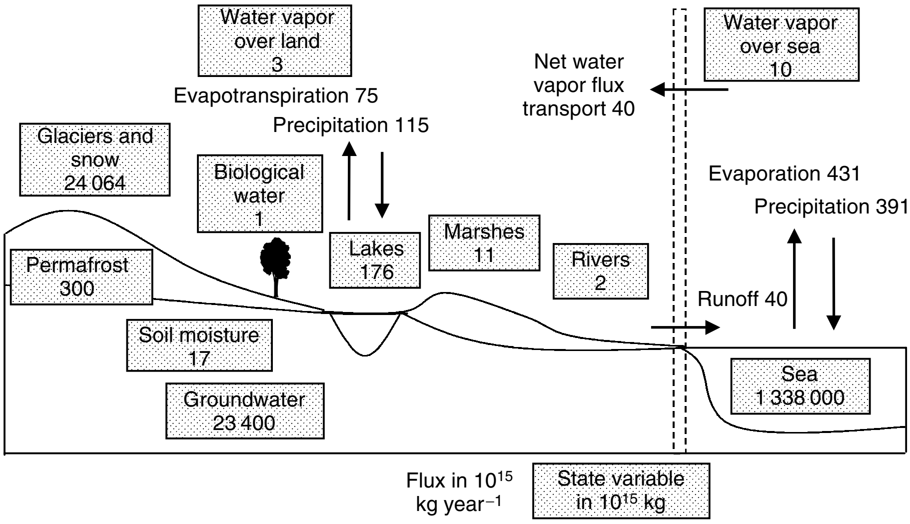

Figure 2 A diagram of the various fluxes and reservoirs within the hydrologic cycle with their yearly average magnitudes (after Oki, 1999) (reprinted with permission of Cambridge University Press). The magnitudes given are approximate, and differ from other authors. For example, see Chahine (1992); Figure 1 for comparison

concentration in the rock and soil is sufficient for withdrawal by pumping. Groundwater for human activities is contained primarily in the aquifer. In this saturated zone, all available spaces within the rock and soil are filled with water. Between the aquifer and soil moisture lays an unsaturated intermediate (vadose) zone that has a lesser influence on the atmosphere than soil moisture. Despite the great societal importance of groundwater supplies, quality spatially distributed subsurface data are elusive.

Land Surface

Water on land can be contained in lakes and marshes as well as rivers and within living organisms (biological water). The volume of water stored on land is relatively small, but the flux of water throughout these systems is relatively high. The relevance of this water to human activities is paramount.

In the broadest sense, the *major fluxes* between reservoirs are:

Precipitation

Precipitation is the fall of solid or liquid water over land and oceans, and is the major driver of the hydrologic cycle over land. Hydrologists have traditionally recognized precipitation as the start of the hydrologic cycle because all other hydrologic phenomena (e.g., evaporation, runoff,

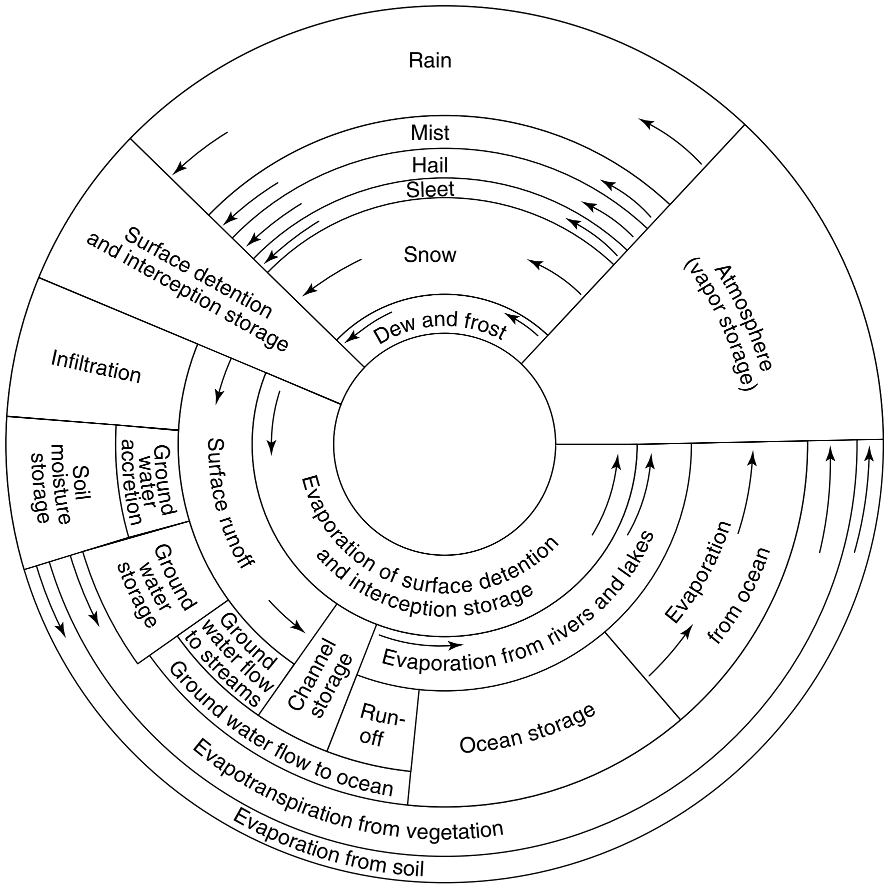

Figure 3 A conceptual diagram of the hydrologic cycle (after Wisler and Brater, 1959). (Reproduced by permission of John Wiley & Sons)

recharge) result from it. The importance of precipitation to the hydrologic cycle cannot be overstated.

Evapotranspiration

Evaporation is the return of water from bare soil or open bodies of water (mainly the ocean surface) to the atmosphere. Transpiration is the transfer of water to the atmosphere through the stomata of vegetation. Collectively, they are considered evapotranspiration.

Runoff

Runoff is the transport of liquid water across the surface of the Earth. Excess water in saturated soils flows into rivers to the ocean, to terminal lakes or swamps. Groundwater can interact with streamflow in rivers if the water table is near the surface.

Water Vapor Transport

Atmospheric water vapor transport is the redistribution of atmospheric water vapor. Globally, there is a net transfer from over ocean to over land. This process is known as advection, and this flux is the major source of water vapor for precipitation over land, aside from recycling.

DESCRIPTIONS OF THE HYDROLOGIC CYCLE

Mathematical Models

Mathematically, the movement of water throughout the hydrologic cycle can be described using the hydrologic continuity equation:

$$\mathrm{I} - \mathrm{O} = \frac{\Delta \mathrm{S}}{\Delta \mathrm{t}} \tag{1}$$

where input (I) and output (O) depend on the reservoir in question (e.g., evapotranspiration is an input to the atmosphere, whereas precipitation is an output). The change in storage (S) in time describes the removal from or addition to present supplies to make up for the imbalance between input and output (in the case of the atmosphere, change in storage would signify a change in specific humidity).

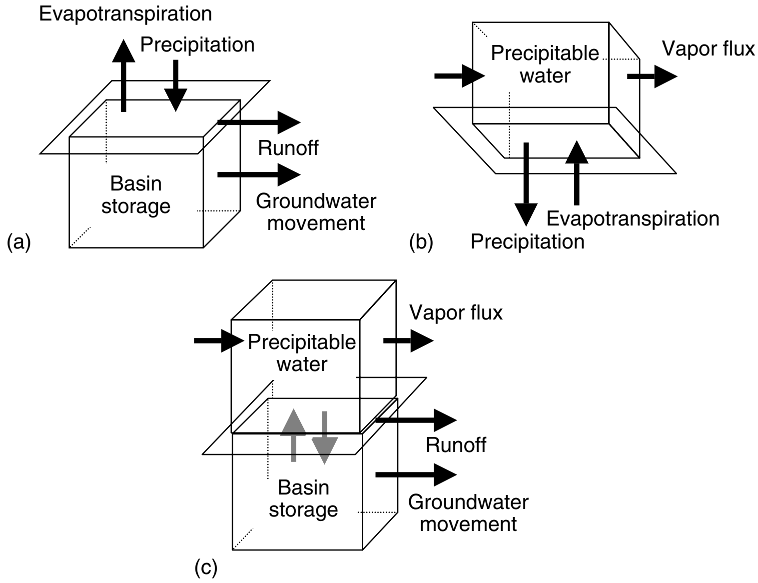

Figure 4 Mathematical schematic of a water balance for: (a) the land surface; (b) the atmosphere; and (c) the combined atmosphere and surface (from Oki, 1999). (Reprinted with permission of Cambridge University Press)

In contrast to the atmosphere, the water balance of a surface portion of a river basin is considerably more complex. Water is input into this system through precipitation, surface runoff, and groundwater inflow from other parts of the basin. Water is lost through surface runoff, groundwater outflow, and evapotranspiration. The change in storage is reflected in changes in soil moisture content. A graphical depiction of a water balance for a portion of the atmosphere and land surface is shown in Figure 4.

On a global basis, the Earth is effectively a closed system, and the amount of water present remains relatively constant (i.e., $\Delta S/\Delta t \approx 0$). However, input and output rates of the hydrologic cycle vary regionally and on a wide range of time scales. Describing, quantifying, and predicting these variations are, in essence, major tasks in contemporary hydrology.

To describe and predict variations within the hydrologic cycle, considerable effort has been invested in developing computer-based numerical models of hydrology and climate. Every component of the climate system has its own models (from groundwater to oceanography and the atmosphere to the land surface) and, within disciplines, there are too many different models to be completely described here. For example, surface hydrologic models range from simple statistics, to regression models (such as the antecedent precipitation index and the soil conservation service curve number model) to more complex conceptual rainfall-runoff models (like the Sacramento model) and finally to the physically based distributed models such as HEC-1 and KINEROS. The spatial and temporal scales of their applications vary from model to model, but ranges from tens to thousands of square kilometers and from minutes and hours to days and years, respectively (Sorooshian *et al.*, 1996). The most complex models available are general circulation models (GCMs; *see* **General Circulation Models (GCMs)**, Volume 1), which have full global representations of the ocean, atmosphere, cryosphere, and land surface. Most of the early work on GCMs related to refining the treatment of the ocean–atmosphere interface. Recently, increasing emphasis has been put upon the land surface–atmosphere interface, improving such models as the Biosphere Atmosphere Transfer Scheme and the Simple Biosphere model (*see* **Land Surface**, Volume 1). Lau *et al.* (1995) compared the ability of 29 GCMs in simulating various aspects of regional hydrologic processes and found them insufficient for use in climate studies related to continental scale water balance. Regardless, this is an area of very active research and as computing power rapidly increases in the near future, one can expect these models to improve.

Data

To date, there are several definitive works providing quantitative descriptions of the global hydrologic cycle (for example, Korzun, 1978; Piexoto and Oort, 1992; Oki, 1999). The most comprehensive review of freshwater resources (supply and use) can be found in Shiklomanov (1999) http://espejo.unesco.org.uy/ and Shiklomanov (1997) http://pangea.upc.es/orgs/unesco/webpc/world_water_resources.html. Earlier works quantifying the complete water cycle have attempted analysis using sparse measurements; the creation of re-analyzed data sets by the European Center for Medium-Range Weather Forecasts and the National Center for Atmospheric Research

(NCAR)/National Center for Environmental Prediction (NCEP) represents a significant advance to these kinds of studies. These data sets blend measurements from rawinsondes, satellite temperatures and moisture, cloud track winds, surface observations by ships, ocean buoys, land stations, aircraft reports, and GCM analysis of atmospheric dynamics. At present, reanalyzed data sets represent the best available global atmospheric water balance measurements.

Quality measurements of individual components of the hydrologic cycle also exist (*see* **Earth Observing Systems**, Volume 1). In particular, global records of precipitation and streamflow are maintained by the Global Precipitation Climatology Center (GPCC; http://www.dwd.de/research/gpcc/) and the Global Runoff Data Center (GRDC http://www.bafg.de/grdc.htm), respectively. Within the US, precipitation records are available from the National Climatic Data Center (NCDC; http://www.ncdc.noaa.gov/), and runoff is available from the US Geologic Survey (USGS; http://www.water.usgs.gov). Of all surface hydrologic variables, precipitation and runoff are the best measured, whereas data quality is considerably lower for other variables, such as snow, soil moisture, and evapotranspiration (Sorooshian *et al.*, 1996). One of the greatest barriers to adequately measuring the hydrologic cycle is the lack of spatially distributed data. Radar and satellite measurements (e.g., the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN) system, Sorooshian *et al.*, 2000) hold great promise in overcoming this barrier, but many of their benefits have yet to be fully realized.

OBSERVED CLIMATOLOGY

The quantities of water contained within the different components of the Earth's system are listed in Table 1. The vast majority of the Earth's total water is contained in the oceans (96.5%, 1.34 billion km^3). The atmosphere contains a relatively small amount of the Earth's total water (0.001%, 12 900 km^3). Of the water not in the ocean (3.5%, 52 million km^3) and if the amount of water contained in polar ice caps and saline waters is excluded, only 15 million km^3 (31% of fresh, 0.8% of total) remain. If the water on the Earth fitted proportionately within a 200-liter (45 imperial gallon) barrel, the water contained in the atmosphere would fill just under half a liter, and freshwater

Table 1 Distribution of water on Earth[a]

Form of water	Area covered (1000 km^2)	Volume (1000 km^3)	Share of world reserves of total water (%)	Share of world reserves of fresh water (%)
World ocean	361 300	1 338 000	96.5	–
Total groundwater[b] (saturated and vadose)	134 800	23 400	1.7	–
Predominantly fresh groundwater	134 800	10 530	0.76	30.1
Soil moisture	82 000[c]	16.5	0.001	0.05
Glaciers and permanent snow cover	16 000	24 000	1.74	68.7
Antarctica	14 000	22 000	1.56	61.7
Greenland	1800	2300	0.17	6.68
Arctic islands	230	83.5	0.006	0.24
Mountainous areas	220	40.6	0.003	0.12
Ground ice in zones of permafrost strata	21 000	300	0.022	0.86
Water reserves in:				
Lakes	2000	180	0.013	–
Fresh water	1240	91	0.007	0.26
Salt water	820	85	0.006	–
Marsh water	2700	11.5	0.0008	0.03
Water in rivers	148 800[d]	2.12	0.0002	0.006
Biological water	510 000	1.12	0.0001	0.003
Atmospheric water	510 000	12.9	0.001	0.04
Total water reserves	**510 000**	**1 390 000**	**100**	–
Fresh water	148 800	35 000	2.35	100

[a] The individual number and column totals may not exactly agree due to rounding. Table modified from Korzun (1978) (reproduced by permission of the United Nations Educational, Scientific and Cultural Organization).
[b] Not including groundwater reserves in Antarctica, broadly estimated at 2 million km^3.
[c] Soil moisture is the water contained within the top 2 m of soil. This does not include ice and snow covered land areas, permafrost regions and arid and semi-arid areas (which collectively cover approximately 65.5 million km^2).
[d] The area of rivers here is the entire land surface. The true area of rivers, in the sense of channels with flowing surface water, is extremely small (<1 million km^2).

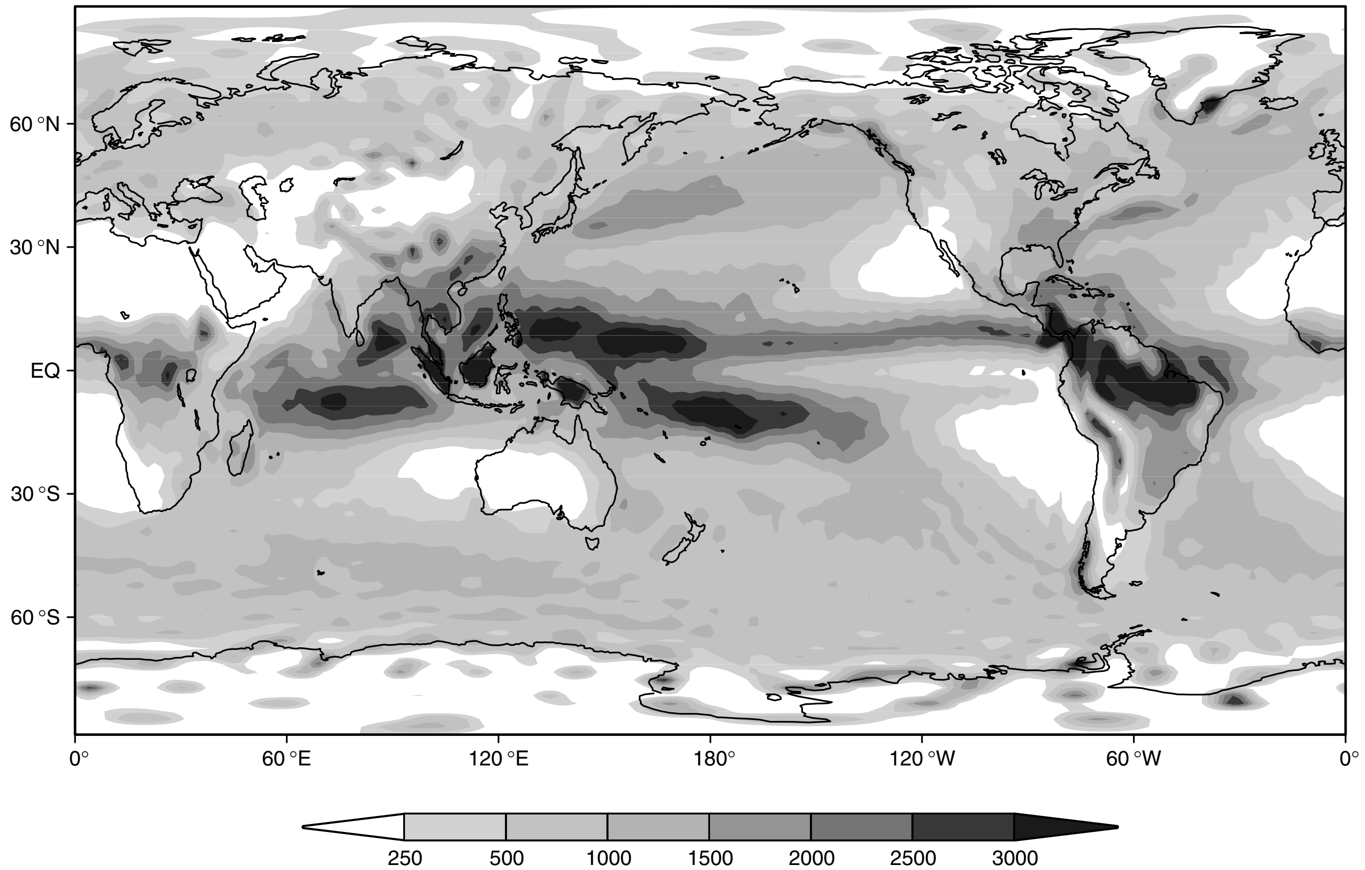

Figure 5 Yearly average precipitation from the NCAR/NCEP re-analysis of data from 1979–1995. Data are shown in mm $year^{-1}$. (Data provided by S Williams of UCAR)

lakes would fill a tablespoon. The water of all the Earth's rivers, from the Nile to the Amazon and the Yangtze to the Mississippi, would fit in the eye of a needle.

The average rate of exchange between the various components can be derived from Figure 2. The residence time (the average length of time that an element of water would spend in a component before moving on) is the total storage of the component divided by the rate of flux out of the component. For example, the residence time of water in the atmosphere is less than 10 days, whereas the ocean has a residence time of over 3200 years (longer for deep parts of the ocean). Depending on the aquifer, residence times for deep groundwater can be very long (>10 000 years). On human time scales, many groundwater supplies can be effectively considered non-renewable. Measurements of residence times are important in detecting, for example, an intensification of the hydrologic cycle associated with climate change. This intensification would appear as a decrease in the residence time of water in the atmosphere.

There is considerable spatial variation within the hydrologic cycle. Precipitation is generally higher in the tropics and along mid-latitude storm tracks (Figure 5). Precipitation patterns also vary by season, following the migration of the intertropical convergence zone, storm tracks, and monsoon systems. Global average precipitation is approximately 970–1000 mm $year^{-1}$, where average precipitation over the ocean is roughly 1100 mm $year^{-1}$ and over land is 700–750 mm $year^{-1}$ (Table 2). The average annual local precipitation rate can be as high as 13 300 mm $year^{-1}$ in Lloro, Columbia and as low as 0.76 mm $year^{-1}$ in Arica, Chile (US Army Corp of Engineers, 1997), although there are dry valleys in the interior of Antarctica that are believed to have not experienced rainfall in the last 2 million years. Globally, precipitation and evaporation are approximately in balance, although the ocean is considered a source for the atmosphere with average evaporation-precipitation being 110 to 130 mm $year^{-1}$, and the land is considered a sink at −260 to −310 mm $year^{-1}$ (Figure 6).

The numbers presented here are not exact and may disagree with those of other authors, emphasizing the level of uncertainty present when computing a water balance. The disagreement between authors can become large at finer spatial scales. For example, comparisons of two authors' estimates of precipitation, evaporation, and runoff by continent and ocean are presented in Table 2.

Table 2 Estimates of average annual precipitation (P), evaporation (E), runoff rate (P − E), river runoff rate (R_0) from continents to oceans, and runoff ratio ((P − E)/P). For comparison, the estimates of Sellers (1965) have been added in parentheses[a]

Region	Surface area (10^6 km^2)	P (mm year^{-1})	E (mm year^{-1})	P − E (mm year^{-1})	R_0 (mm year^{-1})	(P − E)/P
Europe	10.0	657 (600)	375 (360)	282 (240)		0.43
Asia	44.1	696 (610)	420 (390)	276 (220)		0.40
Africa	29.8	696 (670)	582 (510)	114 (160)		0.16
Australia	8.9	803	534	269		0.33
North America	24.1	645 (670)	403 (400)	242 (270)		0.38
South America	17.9	1564 (1350)	946 (860)	618 (490)		0.40
Antarctica	14.1	169 (30)	28 (0)	141 (30)		0.83
All Land Areas	**148.9**	**746 (720)**	**480 (410)**	**266 (310)**		**0.36**
Arctic Ocean	8.5	97 (240)	53 (120)	44 (120)	307	0.45
Atlantic Ocean	98.0	761 (780)	1133 (1040)	−372 (−260)	197	−0.49
Indian Ocean	77.7	1043 (1010)	1294 (1380)	−251 (−370)	72	−0.24
Pacific Ocean	176.9	1292 (1210)	1202 (1140)	90 (70)	69	0.07
All Oceans	**361**.1	**1066 (1120)**	**1176 (1250)**	**−110 (−130)**	**110**	**−0.10**
Globe	**510.0**	**973 (1004)**	**973 (1004)**	**0 (0)**		**0**

[a] Over land, the runoff ratio represents the fraction of precipitation that contributes to runoff. A balance is achieved between P − E and R_0 for various ocean basins via currents between the oceans. Table modified from Piexoto and Oort (1992). (Reproduced by permission of Springer-Verlag).

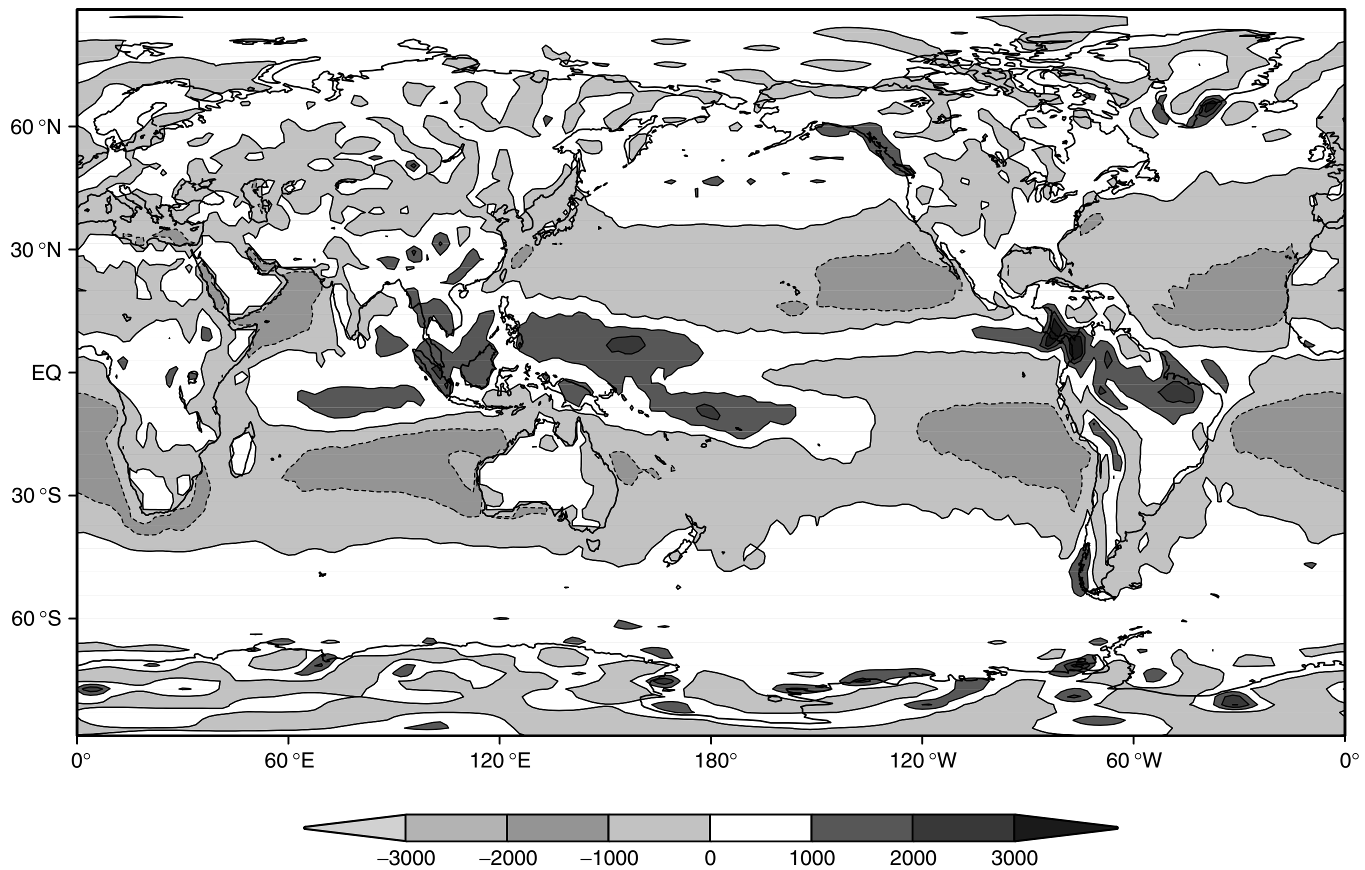

Figure 6 Yearly average precipitation-evaporation from NCAR/NCEP re-analysis data in millimeters year^{-1}. See also Figure 5

VARIATIONS IN THE HYDROLOGIC CYCLE

Although general descriptions of the hydrologic cycle (such as those presented at the beginning of this article) make it seem relatively simple, once one starts to consider the smaller-scale aspects of the hydrologic cycle, it is, in reality, quite complex. Variations within the hydrologic cycle span a wide range of spatial and temporal scales. There are distinct seasonal variations to precipitation and evaporation, and fluxes within the hydrologic cycle vary with latitude and by continent, as stated earlier. However, precipitation also varies with altitude and orientation to local mountains, creating an enormous diversity of microclimates across the globe. Likewise, local weather conditions can change in a matter of minutes, leading to punctual events such as flash floods and microbursts, or they can evolve very slowly, such as long-term drought. Several studies have detailed the static aspects of the global hydrologic cycle, and the interesting new questions in hydrology and meteorology concern the hydrologic cycle as a dynamic system operating and interacting at a variety of scales. What causes drought? What makes one winter wetter or drier than any other? What are the implications of climate change for extreme events? All of these are questions facing researchers today.

One of the areas of increasingly more active research concerns variations within the Earth's climate on interannual, interdecadal, and longer time scales. Prior to the 1970s, solar variations were the most common natural explanation for year to year variations in climate and the hydrologic cycle. Streamflow of certain rivers could be correlated with various sunspot cycles, such as the 11-year cycle. Coincidentally, the earliest attempts at climate forecasting at the turn of the century were born out of attempts to link sunspot cycles with the periodicities found in climate time series, such as Indian monsoon rainfall (the variability of which is now known to be influenced by El Niño (*see* **El Niño**, Volume 1). However, the predictive skill of sunspot–climate relationships is low, and the relationships are unstable in space and time (Korzun, 1978; Allan *et al.*, 1996).

In recent decades, scientists have developed an appreciation for the relationship between the ocean and the atmosphere, in particular how seasonal patterns of local climate can be affected by ocean temperatures in remote areas (also known as teleconnections following Bjerknes, 1969). The El Niño/Southern Oscillation (ENSO, *see* **El Niño/Southern Oscillation (ENSO)**, Volume 1) cycle is the most widely studied of this type of phenomenon. Recent large events have occurred in 1982–1983 and 1997–1998. The ENSO cycle is a coupled variation of the ocean and atmosphere in the tropical Pacific that impacts precipitation in many locations across the globe, from Peru to Africa, Australia and the US, among others (Ropelewski and Halpert, 1987). During warm ENSO events, ocean temperatures become warmer than usual in a region about the size of the US, extending from the coast of Peru to across the international dateline. This warming causes shifts in the patterns of convection in the tropics and, in turn, impacts the global atmospheric circulation. This favors seasonal precipitation anomalies in specific regions, such as floods and droughts. During cold ENSO events (La Niña), the same region of the ocean becomes colder than usual, and the global impacts are generally but not exactly opposite to those of warm ENSO events. These events occur irregularly every two to eight years and can last from one to several years. The breadth and magnitude of variations in the Earth's climate due to ENSO are second only to the changing of the seasons (Allan *et al.*, 1996). Predictions of ENSO have contributed successfully to seasonal forecasts of precipitation, which, in turn, can be very useful for water management (for example, Changnon and Vonnhame, 1986; Stern and Easterling, 1999; Changnon and Bell, 2000).

Variations and teleconnections on longer time scales also have major impacts on the hydrologic cycle. Two phenomena that have received considerable attention and research are the North Atlantic Oscillation (NAO, *see* **North Atlantic Oscillation**, Volume 1) and the Pacific Decadal Oscillation (PDO, *see* **Pacific–Decadal Oscillation**, Volume 1). The PDO concerns ocean temperature variations in the northern Pacific, whereas NAO concerns the northern Atlantic Ocean and atmosphere. The PDO operates on a time scale of 20–30 years, with observed shifts in the 1890s, 1920s, 1940s, 1970s and possibly the mid-1990s. The various phases of the PDO have been associated with wet and dry periods in North America and can serve to enhance or cancel the effects of ENSO, depending on their states. The NAO exerts a considerable influence on the hydroclimatology of Europe, Northern Africa, and the Middle East, among other regions. There is some evidence supporting the idea that variations in the North Pacific and North Atlantic are coupled and should be thought of as two manifestations of a single underlying phenomenon. Developing predictors of both of these oscillations remains an area for active research.

On centennial scales and longer, the hydrologic cycle has changed in both subtle and dramatic ways. Changes in the orbital parameters of the Earth with respect to the Sun have been responsible for glacial periods in the Earth's history. During glacial periods, the extent of glaciers increases to much more than that of today. For example, during the most recent glacial maximum 20 000 years before the present interglacial, Chicago lay beneath more than 1 km of ice. Changes in the Earth's temperature and the volume of water trapped in glaciers caused the sea level to be about 100 m lower than today, drying up the English Channel. Clearly, large-scale weather patterns were altered, changing patterns of precipitation and the partitioning of precipitation into rain and snow. Likewise, continental streamflow would have increased as the glaciers melted. Changes in streamflow can impact ocean circulation. As the glaciers retreated from the most recent glacial maximum, and their waters released into the North Atlantic, the density of ocean surface water was reduced, and the formation of deep ocean water in this region was halted. As a result, Europe's temperature and hydrology was much different than today. On climate time scales, this switching was extraordinarily rapid, on the order of decades (*see* **Thermohaline Circulation**, Volume 1; **Younger Dryas**, Volume 1).

Aside from ocean and atmospheric variability, the land surface itself can impact precipitation in local and remote areas. Variations in soil moisture influence precipitation due to the amount of moisture that is recycled over land. Chahine (1992) estimated that a full 65% of land-falling precipitation comes from evaporation over the land, most of it advected in from other locations (see Trenberth, 1999a for further discussion on evaporation and moisture recycling). The amount of moisture available, as well as its spatial distribution, is important, even at fine scales; sharp soil–moisture gradients have been known to influence the development of tornadoes, for example. Discontinuities in soil moisture, such as those found at the interface between irrigated agriculture and native vegetation, tend to enhance shallow convective precipitation.

Vegetation also regulates the availability of soil moisture to the atmosphere through the opening and closing of plant stomata. Changes in surface vegetation can induce changes in local meteorology and climate. In particular, decreases in precipitation are believed to be associated with changes in land cover in south–east Asia and the Amazon (and in Africa; *see* **Land Cover and Climate**, Volume 1). Charney (1975) found that the absence of significant moisture sources might help to maintain deserts. In other words, the lack of local moisture for recycling purposes makes a desert a stable system and that, once an area has been made into a desert, it is difficult to change without external forcing (*see* **Deserts**, Volume 1).

HUMANS AND THE HYDROLOGIC CYCLE

One component of the hydrologic cycle that is frequently not directly included in its descriptions is human activity. The hydrologic cycle would continue, irrespective of human activities, but humans do have a significant impact on the terrestrial component of the hydrologic cycle. Likewise, changes in the hydrologic cycle can dramatically impact human activities, for better or for worse. Under growing population pressures, decreasing availability of freshwater per person, and potential global climate change, how this feedback will develop in coming years remains an interesting yet unresolved question.

Are humans affected by the hydrologic cycle? Certainly. Water is essential to life on Earth. The availability of water has shaped where civilizations have developed and thrived, just as lack of water has caused great hardships. Water is both a necessity and a resource for financial gains. Yet, while it is a benefit, it is also a hazard. On average, over $8 billion damages per year have resulted from flooding and hurricanes in the US alone (Kunkel *et al.*, 1999). Indeed, this does not include pandemic health hazards created by poor water quality.

Will humans affect the hydrologic cycle in the future? Undoubtedly. There is considerable evidence that humans have affected the hydrologic cycle in the past (Figure 7). Large dams, reservoirs, and extensive canal systems are perhaps the most visible testimony to this. In several basins across the globe, surface water resources have been so intensively developed that major rivers periodically cease flowing to the ocean (such as the Colorado River in the US and the Yellow River in China). Inter- and intra-basin transfers have significantly interfered with the natural distribution of water.

The most pervasive change to the hydrologic cycle due to human activities is associated with land-use change. These changes are very important to consider as, according to van Dam (1999, xiii), "the effects of climate variability and change on the hydrological cycle will be coincident with those of changes in land use, which could be of the same order of magnitude." The various types of land-use changes range from deforestation to agriculture, urbanization to draining swamplands. The impact of these land uses on streamflow is presented in Table 3. The impacts arise from changes in surface albedo, surface roughness, surface permeability (the ability of water to pass through a surface, such as concrete), and the ability of the surface to intercept and evaporate moisture. These impacts are inherently scale-dependent, and most local land-use change will not have a major impact on the continental and global hydrologic cycle. However, the extent of land-use change in total is considerable; Flohn (1973) suggested that, over the last 8000 years, approximately 11% of the land surface has been converted to arable land, and 31% of forests have been modified from their original condition. Additionally, certain regions are poised to have a disproportionately strong impact on global circulation. For example, there is debate as to whether Amazon deforestation will have an impact on tropical and extratropical climate out of the region. Although this is an area of active research, the expected long-range impacts from Amazon deforestation outside the region remain unclear (Gash and Nobre, 1996).

While global fluxes or distributions of water may not be influenced by water quality, humans significantly impact water quality at every step of the hydrologic cycle. Since the 1970s, the primary atmospheric water quality concern has been acid rain. Acid rain damages trees, particularly at high elevations, and contributes to the acidification of lakes and streams. Regions already affected include North

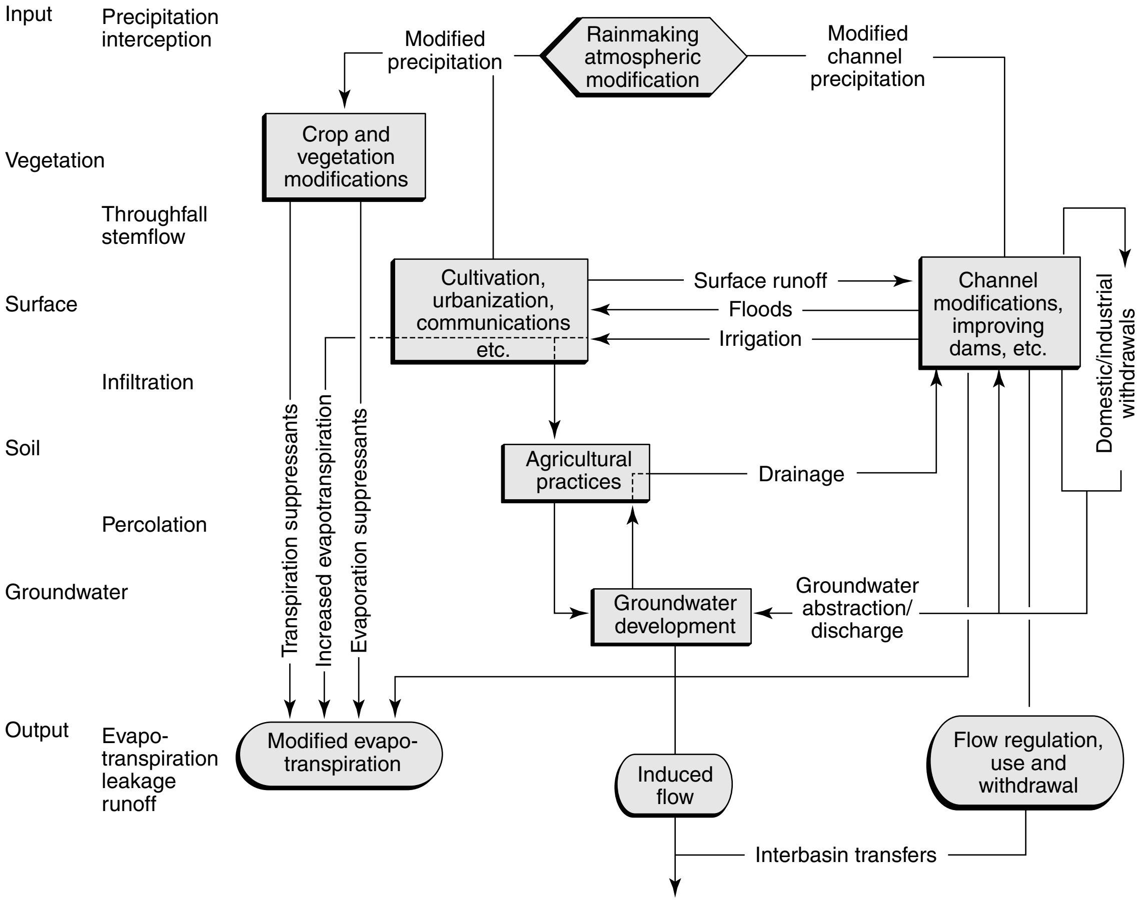

Figure 7 Systems diagram of the impacts of human activities on streamflow (from Ward, 1990). (Reproduced with the permission of McGraw-Hill Publishing Company)

America and Northern Europe. Contamination of water at and below the land surface poses a significant threat to potable water supplies (see Fetter, 1998 and Bedient *et al.*, 1999 for further reading on groundwater contamination). Water quality can be affected by human activities in a multitude of ways, including effluent, leeching from landfills, industrial and mining activities, and agricultural fertilizer and pesticide runoff. In particular, the long-term isolation of hazardous radiological byproducts from water supplies poses a special challenge.

GLOBAL CLIMATE CHANGE AND THE HYDROLOGIC CYCLE

As mentioned previously, the magnitude of the impact of human activities on the hydrologic cycle is highly scale-dependent, and few activities manifest themselves on a global scale. However, the extra release of carbon dioxide (CO_2) into the atmosphere and the resulting possible changes in the hydrologic cycle are the subject of a considerable amount of research effort and political attention. A summary of these changes is provided in Table 4. While there is some uncertainty and debate concerning global warming, the theory as to why the hydrologic cycle may be affected is relatively straightforward.

Greenhouse gases in the atmosphere reflect and re-radiate outbound long-wave radiation back to the Earth's surface, increasing the surface temperature. CO_2 is one such gas, while water vapor, methane, and nitrous oxide are among some of the others. The relationship between the concentration of CO_2 in the atmosphere and the temperature of the Earth has been thoroughly documented on geologic time scales. For instance, during the last glacial period when the atmospheric CO_2 concentration was closer to 200 parts per million by volume (ppmv), the Earth was 6–8 °C cooler than during pre-industrial conditions of 280 ppmv. The current atmospheric concentration of CO_2 is about 370 ppmv, and predictions of future concentrations range from 450–1000 ppmv in the year 2100. The anticipated increase in global surface temperatures over this period is from 1.4 to 5.8 °C (IPCC, 2001).

If the amount of long-wave radiation reflected back to the Earth's surface is increased, the potential evaporation from

Table 3 Summary of impacts of land-use changes[a]

Land use change	Component affected	Principal hydrologic process involved	Geographic scale and likely magnitude of effect
Afforestation (deforestation has converse effect, except where disturbance caused by forest clearance may be of overriding importance)	Annual flow	Increased interception in wet periods; delay in spring runoff; Increased transpiration in dry periods through increased water availability to deep root systems	Basin scale; magnitude proportional to forest cover. On average, conversion of 10% of watershed area to forest cover results in 34 mm $year^{-1}$ reduction in annual flow per unit area
	Seasonal flow	Increased interception and increased dry period transpiration will increase soil-moisture deficits and reduce dry season flow	Basin scale; can be of sufficient magnitude to stop dry season flows
		Drainage activities associated with planting may increase dry season flows through initial dewatering and also through long term-effects of the drainage system	Basin scale; drainage activities will increase dry season flows
		Cloud water (mist or fog) deposition will augment dry season flows	High-altitude basins only; increased cloud water deposition may have a significant effect on dry season flows
	Climate	Increased evaporation and reduced sensible heat fluxes from forests affect climate	Micro, meso, and global scale; forests generally cool and humidify the atmosphere
Agricultural intensification	Water quantity	Altering of transpiration rates affects runoff	Basin scale; effect is marginal
		Timing of storm runoff altered through land drainage	Basin scale; significant effect
Draining wetlands	Annual flow	Initial dewatering following drainage will increase annual flow	Basin scale; effect may last from one to two years to decades
		Afforestation following drainage will reduce annual flow	Basin scale; effects as for afforestation
	Seasonal flow	Upland peat bogs, groundwater fends, and African dambos have little effect in maintaining dry season flows	Basin scale: drainage or removal of wetland will not reduce and may increase dry season flows
		Lowering of the water table may induce soil–moisture stress, reduce transpiration, and increase dry season flows	Basin scale; a reduction of water-table depth to a minimum of 30 cm below surface is required
		Initial dewatering following drainage will increase dry season flows	Basin scale; effect may last from one to two years to decades
		The deeper flow outlet of the drainage system will lead to increased dry season flows	Basin scale; effects will be long-term
Urbanization	Runoff volume	Impervious surfaces such as paved roads, roofs, and parking lots increase surface runoff during storm events and decrease groundwater recharge	Basin scale; magnitude of effect depends on extent of urbanization

[a] Table modified from Calder (1993) with additional data from Urbonas and Roesner (1993). (Reproduced by permission of McGraw-Hill Publishing Company).

Table 4 Best estimates of climate change projections over the next 50–100 years

Indicators	Annual average change	Distribution of changes		Interannual variability	Significant transients	Confidence of projection	
		Regional average	Change in seasonality			Global average	Regional average
Temperature	+1 to +3.5 °C	−3 to +10 °C	Yes	Down?	Yes	High	Medium
Sea level	+15 to +95 cm	–	No	?	Unlikely	High	Medium
Precipitation	+7 to +15%	−20 to +20%	Yes	Up	Yes	High	Low
Direct solar radiation	−10 to +10%	−30 to +30%	Yes	?	Possible	Low	Low
Evapotrans-piration	+5 to +10%	−10 to +10%	Yes	?	Possible	High	Low
Soil moisture	?	−50 to +50%	Yes	?	Yes	?	Medium
Runoff	Increase	−50 to +50%	Yes	?	Yes	Medium	Low
Severe storms	?	?	?	?	Yes	?	?

Source: Schneider *et al.* (1992) (reproduced by permission of John Wiley & Sons) and S Schneider (personal communication, July 27, 2000).

the ocean and the land surface may also increase. Likewise, because warmer air can potentially hold more water (the amount of water that it would take to saturate a parcel of air increases exponentially with temperature), humidity may increase. If the increase in water vapor storage in the atmosphere does not balance the increased evaporation, precipitation rates should change, on the average (*see* **Water Vapor: Distribution and Trends**, Volume 1). Due to complex feedbacks within the Earth's climate system, the anticipated impacts of global warming on the hydrologic cycle become considerably more difficult to predict beyond these first few conceptual steps. For example, a more vigorous atmospheric water cycle may involve increased low clouds that might reduce the amount of incoming radiation to the Earth's surface, leading to negative feedback and cooling. However, an increase in high clouds, which are efficient at reflecting long-wave radiation back to the Earth's surface while letting short-wave radiation pass through, would lead to positive feedback of further warming.

If understanding the impact of climate change on all aspects of the hydrologic cycle is difficult, translating these impacts into their effects on human activities is an even greater challenge. Humans are most sensitive to hydrologic variations, extremes, and certain sequences of events. Such questions as how climate change will affect the occurrence of drought in a particular region remain open to debate (although considerable effort has been devoted towards trying to answer these questions, see National Assessment Synthesis Team, 2000). Some scientists believe that the clearest changes associated with global warming will be in the occurrences of extreme events. Assuming that a climatological variable (e.g., precipitation, temperature) has a normal distribution, changes in the mean will bring proportionally greater shifts in intensity and frequency at the tails of the distribution (Trenberth, 1999b; see also Easterling, 2000a for an excellent discussion of the observed and anticipated changes in extreme events induced by climate change).

The atmosphere is not the only component of the hydrologic cycle that may be affected by global climate change; the ocean and cryosphere may also be impacted. Simulations of climate change have predicted that the greatest warming will occur at high latitudes. Locally, this poses a threat to regions with permafrost, where melting can cause land-surface subsidence and damage to structures. However, if temperatures are warm enough, glacial melt and thermal expansion of the oceans also may cause sea level changes over the next 100 years. This is of concern because a 1% decrease in glacial water content translates to approximately a 30 cm increase in sea level. To help put this in perspective, a 2-m rise in sea level could entirely inundate the Republic of the Maldives. Changes in surface albedo associated in the change from ice to bare ground or open ocean is a positive feedback, associated with increased absorption, higher temperatures, and possibly increased melting. The predictions of sea level increase range from 13–94 cm by the year 2100 (IPCC, 1995). Such a change could have dire consequences for coastal ecosystems.

The response of the hydrologic cycle to climate forcing can also be nonlinear. Large temperature rises at high latitudes, increases in precipitation, and glacial melt may alter the vertical density profile of the North Atlantic Ocean, causing a slowing or collapse of the deep-water formation, greatly impacting the climate of Europe, as was seen during the younger Dryas period. Model simulations of doubling CO_2 concentrations predict a decrease in deep-water formation, with eventual recovery after concentration stabilization, whereas quadrupling concentrations leads to thermohaline collapse and very slow recovery. These simulations are highly model-dependent, but they do emphasize the presence of thresholds and triggers within the climate system (*see* **Climate Change, Abrupt**, Volume 1).

The expected impacts of climate change on surface runoff and groundwater recharge remain unknown, in part due to the fine spatial scale being considered, and unknown changes in seasonality and timing of precipitation. However, the possible ramifications of these changes should not be underestimated. In regions where water resources are fully committed or over-committed, declines in supply can lead to regional disputes and international conflict. A comprehensive database of articles related to water resources and climate change in the US has been compiled and is available at http://www.pacinst.org/CCBib.html.

20TH CENTURY OBSERVED CHANGES IN THE HYDROLOGIC CYCLE

One of the most difficult challenges in detecting changes in the hydrologic cycle is the lack of globally complete, high-quality long-term measurements. In particular, existing observations of soil moisture and evaporation are unsuitable for studies of long-term changes. Likewise, it is difficult to estimate the underlying climatological frequency of rare events (e.g., floods) from existing data sets, much less detect changes in the frequency or magnitude of these events. Attributing the observed changes to human activities or natural variability represents a special challenge in and of itself. Nonetheless, there are some detectable trends in the modern instrumental precipitation data, primarily towards drier conditions in the tropics and wetter conditions in the extra-tropics. Fewer trends have been detected in streamflow. A summary of recent hydrologic trends is presented in Table 5.

A thorough review of the observed global changes in precipitation is provided by IPCC (1995). A review of changes in the US was done by the National Assessment Synthesis Team (2000). Annual precipitation in the US has increased by 5%, primarily in autumn and in the eastern two–thirds of the country. These increases have been associated with modest increases in heavy rainfall events (i.e., $>5\,\mathrm{cm\,day^{-1}}$, Karl *et al.*, 1995). Streamflow trends are consistent with these increases; geographically widespread regions of the US have experienced increases in the annual median and minimum daily flows. This suggests that, overall, there is more water, in general, in US rivers today and that droughts have not been as extreme as they were in the 1950s–1970s (Lins and Slack, 1999). Easterling *et al.* (2000b) found that precipitation extremes are on the rise in many locations across the globe, but reminded us of the danger of drawing firm conclusions based on analysis of relatively short data records. Likewise, recent changes in the frequency of warm ENSO events and the state of the PDO (since the 1970s) have made sole attribution of the observed climate changes to anthropogenic activities difficult.

Table 5 Observed trends in the hydrologic cycle

Variable	Observed trend	Confidence
Ocean		
High clouds	Increase 1951–1981	Low
Mid-level clouds	Increase in Northern Hemisphere, mid-latitude 1951–1981	Low
Convective clouds	Increase 1951–1981	Low
Fair weather cumulus clouds	Decrease 1951–1981	Low
Water vapor	Increase 1973–1988	Low
Evaporation in tropics	Increase 1949–1989	Medium
Land		
Mid- to high-latitude clouds	Increasing 1900–1980s	Medium
Mid- to high-latitude precipitation	Increasing since 1900	Medium
Northern Hemisphere subtropical precipitation	10% decrease since 1970	Medium
Evaporation in US and FSU[a]	Decreasing since 1950	Low
Soil moisture in FSU[a]	Increasing 1970s–1990s	Low
Runoff	Pattern consistent with precipitation changes	Medium

Source: IPCC, 1995. (Reproduced by permission of the IPCC).
[a] Former Soviet Union.

TOWARDS IMPROVED UNDERSTANDING OF THE HYDROLOGIC CYCLE

Although the hydrologic cycle has been studied for well over a century, with considerable work being done in recent decades, many unresolved questions and expanding frontiers in water cycle research remain. In particular, understanding the impacts of human activities on the hydrologic cycle is an area of active research. Considerable effort is also being devoted to understanding the linkages between the ocean and atmosphere in the tropics (such as ENSO), as well as at mid-latitudes (through PDO, NAO, and through changes in ocean thermohaline circulation). Increased attention has been devoted to land surface and hydrologic representation in large-scale computer models, the intent of which is to improve predictions of variations in the hydrologic cycle on interannual and longer time scales. Medium-range weather predictions can also improve through having a better understanding and model representation of soil–moisture processes (Chahine, 1992). Finally, groundwater and surface interactions, ranging from the amount of water recharged into an aquifer from snowmelt to the hydrology of natural springs, are some of the least understood components of basin-scale water balances.

Improved understanding of the hydrologic cycle is not limited to the understanding contained within the scientific research community. It is also that of the operational water management community, the general public, and other water resources stakeholders. Concepts such as climate stationarity (the belief that the underlying statistics of the climate of a particular region are constant in time) are key assumptions for most water management planning and design, although the research community has long recognized the flaws in this assumption. For example, for structural design purposes, relatively brief historical records are used to estimate the magnitude of the flood that would happen once in a 100 years. If the historical period being considered contains unusually wet or dry spells, this approach will not give a representative estimate of what may happen in the future. Likewise, most regions lack legal recognition of the connection between the groundwater and surface-water components of the hydrologic cycle. The impacts of excessive groundwater withdrawals on streamflow are fairly well understood by the scientific research community, although few, if any, regions have laws that reflect this understanding.

There are several major research programs designed to develop a more sophisticated understanding of the hydrologic cycle. One such program, the Global Energy and Water cycle EXperiment (GEWEX, *see* **GEWEX (Global Energy and Water Cycle Experiment)**, Volume 1), was initiated in 1988 by the World Climate Research Programme (WCRP, 1990; Chahine, 1992). Part of GEWEX is designed to observe and model the hydrologic cycle, with the ultimate goal of predicting global and regional climate change. The program includes large-scale field activities and intensive measurements, as well as modeling and research. GEWEX has contributed to the development of improved numerical models and the creation of state of the art climate data sets, and it is also helping to achieve its goals of improving resource management through scientific outreach to the engineering and other user communities.

See also: **Hydrology**, Volume 2; **Water Use: Future Trends, and Environmental and Social Impacts**, Volume 3; **Circulating Freshwater: Crucial Link between Climate, Land, Ecosystems, and Humanity**, Volume 5.

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